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ABSTRACT

This paper responds to an article by John Bruer that questions the wisdom behind the recent surge of interest in the educational implications of brain research. Bruer is skeptical about brain-based educational practice and policy. This paper argues in favor of the default alternative that knowledge of brain functioning and development can guide theory, research, and practice in education. The first section examines Bruer's negative conclusion, including the scope of the neuroscience considered, conservative and reform-oriented perspectives, and communication of scientific results to nonspecialist consumers. It also discusses issues beyond specific knowledge. The second section discusses the default alternative, examining prevention versus remediation in child development and education; critical periods and formative postnatal development; plasticity, flexibility, and stability; and aspects of formative postnatal development. The paper notes that education is not the only field where the brain is becoming an important consideration, and it is important to turn to the brain to discover more about how people learn. It concludes that specialists from diverse fields must join forces to investigate this new challenge as a unified body open to innovations and new discoveries. (Contains 59 references.) (SM)

Brain-Based Education: A Reply to Bruer

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Brain-Based Education: A Reply to Bruer

In his November 1997 Educational Researcher article, "Education and the Brain: A Bridge Too Far," John Bruer questions the wisdom behind the recent surge of interest in educational implications of brain research. He argues that "currently, the span between brain and learning cannot support much of a load. Too many people marching in step across it could be dangerous" (p. 15). Basing his arguments mainly on synaptic development research, he suggests that the "neuroscience and education argument" is premature, and concludes, "we should remain skeptical about brain-based educational practice and policy" (p. 15). This reply discusses Bruer's conclusion and concludes in favor of the default alternative that knowledge of brain functioning and development can guide theory, research, and practice in education. It is argued that Bruer's analysis is selective, understandably, in the neuroscience it considers, but may be accurate if viewed from the conservative perspective that education is direct instruction of culturally transmitted knowledge. By contrast, the recent brain and education movement is reform-oriented with an entirely different mission aimed at pushing educational practice beyond the limits of the traditional knowledge transmission view of education.

Bruer's Conclusion

The Scope of the Neuroscience Considered

Bruer bases his case against the neuroscience and education movement on sensory-system synaptogenesis, especially Greenough's (Greenough, Black, & Wallace, 1987) analysis of the research on synaptic development in rats (Greenough, 1987), cats (Cragg, 1967, 1975a, 1975b), rhesus monkeys (Goldman-Rakic, 1987; Rakic, 1995), and humans (Huttenlocher,

1990; Huttenlocher & de Courten, 1987). This research suggests that synaptic development involves an intense phase of synaptic overproduction (or blooming) followed by an extended phase of synaptic elimination (or pruning). For instance, in the human visual cortex, the average number of synapses per neuron is about 5,000 (40% of the maximum) at 2 months of age. It doubles to more than 10,000 (80%) around 4 months of age, peaks to 15,000 (maximum) in the course of the first year, and begins its steady decline to adult levels of about 10,000 by around age 10 (Huttenlocher, 1990, 1994).

Throughout the target article, Bruer refers to this and other neuroscience research cited in popular educational writing and retrospectively evaluates the adequacy of what is known about brain functioning and development in general. Bruer does not examine the larger literature on the brain perhaps because such investigation might detract from the more immediate focus on the ongoing neuroscience and education argument. Nevertheless, this reasonable consideration leaves unanswered several questions that are central to the ultimate conclusion of the target article about the brain and education alliance. How would the conclusion change if the larger brain and education literature were to be examined? The synaptogenesis research and other related studies may not support the neuroscience and education bridge in its final state, but would they not offer a good place to begin the building of the bridge? Is it possible that brain sciences, if examined, could be a guide in the field of education as life sciences have been, and continue to be, in the field of medicine (see Sylwester, 1995)? Surely, looking at the neuroscience cited in popular educational literature would not turn up all the relevant knowledge necessary to judge the adequacy of what is known

about the brain.

Bruer's final conclusion is indeed about the entire realm of brain sciences. In its title and throughout, the target article uses such statements as the following: "Education and the brain: A bridge too far" (p. 4); "we do not know enough about brain development and neural function to link that understanding directly, in any meaningful, defensible way to instruction and educational practice" (p. 4); and "we should remain skeptical about brain-based educational practice and policy" (p. 15). Whereas these statements clearly presuppose the examination of the larger literature on the brain, the target article reveals very little neuroscience beyond the sensory-system synaptogenesis research that has already made its way into education. As a result, the brain end of the brain-education conclusion simply hangs in midair without support.

Relevant to the conclusion of the target article is the synaptic literature that has not yet completely reached the field of education. The vast body of the data presented by Eric Lenneberg (1967) on critical periods for language development, the research of Eric Kandel (1976) on synaptic plasticity, and the work of the Noble laureate Gerald Edelman (Edelman, 1987; Edelman & Mountcastle, 1978) are particularly noteworthy. Next to these textbook examples of the neuroscience work on synaptic functioning is the closely related literature on the development of myelination and neurotransmitter systems (Dawson & Fischer, 1994; Mize & Erzurumlu, 1996; Reynolds & Janzen, 1989). There is also a substantial body of unexamined brain research in education outside the data on synaptogenesis. For instance, all but one of the chapters in a recent edited volume entitled The Brain, Cognition, and Education

(Freedman, Klivington, & Peterson, 1987) went unnoticed as did the articles in a more recent special issue of Educational Psychologist (Fall 1992) devoted to brain and education.

What is, then, the real source of Bruer's conclusion about the brain and education alliance? Is it how much we really know about brain functioning or the assumption, as of yet unexplored, that the brain is too complex to tackle at this time? In the mid 1970's, the present author once asked Walter Schneider, who was conducting psychological research in the computer-inspired information processing tradition (Schneider & Shiffrin, 1977), *why psychologists and educators paid so little attention to the brain even though it must be the system they should first be trying to understand.* Schneider's response then was the same as Bruer's conclusion today: *we know too little about the brain.* However, today, two decades later, Schneider is doing brain-based educational research at Pittsburgh's LRDC. Those who have given the brain a chance have come to appreciate the extent of its indispensability, relevance, and potential for illuminating the path to understanding learning and behavior.

Conservative and Reform-Oriented Perspectives

Bruer's view of the relationship between neuroscience and education is compelling if examined from a conservative perspective on education and science. His discussion of synaptic development cautions that "in reviewing this work, readers outside the field should be aware of its complexity and methodological issues involved" (p. 6). The reader is advised that the findings, especially those for humans, are highly prone to artifacts resulting from implementation of tedious procedures, coarse measurements, premature extrapolations across species, and similar problems associated with observing change in a rapidly-growing system

like the newborn brain.

On the one hand, Bruer's caution signs are timely and likely to have a favorable impact on the brain and education movement. To be sure, there is much room for improvements in the treatment that some neuroscience findings have received in educational writings. However, general claims about how much is known about the brain and indiscriminate warnings against the entire brain and education movement are equally noteworthy and misleading. Many interested educators may find themselves faced at the outset with the dilemma of having to avoid brain research altogether or abide by the same meticulous guidelines that laboratory neuroscientists must follow when they are counting synapses in brain tissue.

The target article is also conservative in its interpretation of neuroscience findings. Consider the classic Wiesel and Hubel (1965) study cited by both Bruer and supporters of the brain and education alliance. In this study kittens and adult cats were deprived of visual input to one of the eyes. Whereas this manipulation had no influence on adult cats, kittens were irreversibly affected in that for them deprivation led, as Wiesel and Hubel put it, to the virtual blindness of the deprived eye. According to Bruer, the study "has shown that if an animal's sensory and motor systems--that is, systems like vision or tactile discrimination--are to develop normally, then the animal must have certain kinds of experiential input at the specific times during its development" (Bruer, p. 7). Moreover, Bruer convincingly argues that this and other "neuroscientific research on critical periods supports an educational moral or policy recommendation about the importance of diagnosing and treating children's sensory systems" (p. 9). Nevertheless, the target article states that the research has no educational significance

for two reasons. First, the data support critical periods for synaptic development within the realm of sensory systems only. Secondly, when sensory systems are in working order, the range of experiences children need to develop their fundamental sensory-motor capacities are spontaneously available everywhere.

The alternative (reform-oriented) interpretation of this research suggests no line of separation between sensory and nonsensory systems of the brain. This perspective receives some support in synaptogenesis research in brain areas other than sensory systems. For example, in the frontal cortex, the number of synapses per neuron peaks towards the end of the first year, stays high until about age 7 or 8, and begins its steady decline to reach adult levels at about age 16 (Huttenlocher, 1990, 1994, Huttenlocher & de Courten, 1987). One finds only passing reference to this research in the target article. The sensory-nonsensory distinction is based on the research of Greenough and his colleagues (Greenough et al., 1987). An important feature of Greenough's distinction, also evident in the target article, is that sensory-systems synaptogenesis, but not synaptic development in the central nervous system, involves critical periods. The general conclusion in the target article about synaptic development research is that "all this very interesting neuroscience provides little guidance or insight for educators" (p. 8).

Another major difference between conservative and reform-oriented perspectives has to do with the role of learning environments. The idea that even monotonous, impoverished, and boring environments universally carry what is needed for normal synaptic growth in the sensorimotor systems (Bruer, 1987; Greenough, 1987) is a reassuring indication of the degree

of resilience of the sensory capacities of infants. Equally resilient also are the capacities of infants, as well as children, to take advantage of environmental opportunities for novelty, variety, and challenge, when these are available spontaneously or otherwise. However, "educational moral and policy recommendations" for ensuring the normal or enhanced availability of these and other favorable learning conditions are no less urgent or significant than those of diagnosing and treating sensory problems. In fact, a venerable body of research indicates that stimulus novelty is a fundamental modulator of sensory attention during infancy (Fantz, Fagan, & Miranda, 1975). For instance, a combination of preference for novelty scores at 4 months and mother's education predicted 43% of the variance in intelligence at age 5 for a sample of 19 preterm and 9 full-term children (O'Connor, Cohen, & Parmelee, 1984). Similarly, visual novelty scores at 6 months and parental education accounted for 28 to 43% of the variance in later intelligence scores (Molfese & Molfese, 1994; Rose & Wallace, 1985a, 1985b). These data may be interpreted as an indication that the sensory and central capacities of infants are not as different and separate as a conservative interpretation of the synaptogenesis research might impy. The research of Huttenlocher and colleagues (Huttenlocher, 1990, 1994, Huttenlocher & de Courten, 1987) on synaptic development in the frontal cortex is consistent with this alternative.

Finally, the target article also adopts a conservative perspective on the role and mission of education. Within the scope of this mission, brain research is educationally relevant only if it translates into direct instruction or knowledge transmission. According to Bruer, "currently we do not know if critical periods do or do not exist for culturally transmitted knowledge

systems--reading, arithmetic--that children acquire through informal social interaction and formal school instruction" (p. 8). Whether educators ought to expect neuroscience to reveal critical periods for traditional curriculum areas or "pre-packaged" strategies for teaching them is an interesting subject for debate between conservative and reform-oriented educators. It should not be the basis for a definitive negative conclusion about the neuroscience and education alliance in general. From an educational-reform perspective, searching for such word-for-word translation of neuroscience into educational practice might only amount to setting ourselves up for discouragement from the outset--"we may never know enough . . ." (Bruer, p. 4). Reading and arithmetic are complex domains. They are likely to involve the sensory (e.g., the visual context) as well as nonsensory (e.g., the frontal cortex) brain areas. We may ask why the neuroscientific knowledge of synaptic development in central brain areas should be considered useless for educators?

These conservative aspects put Bruer's view of education at odds with the very mission of the reform-oriented neuroscience and education movement (Alcock, 1997; Caine & Caine, 1995; Sylwester, 1995): to alert parents and caregivers to be not just informationally but also emotionally available to children; to guide the schools to do more than direct instruction of the subject matter; to inform educators that children's brains are not just reservoirs for stored knowledge; to help teachers to go beyond the entrenched practices of the traditional knowledge-transmission model; and to encourage us all to pay more attention to other developmental needs of children during the formative years of postnatal development. The target article overlooks this overt goal of the neuroscience and education movement.

It is no coincidence that Bruer's conservative view of education and Greenough's neuroscience have so much in common: they both rely on the computer-inspired version of information-processing theory, the one that views learning as extracting specific knowledge from the environment for storage in the brain hardware. Greenough assumes that beyond sensory-system development, there is the learning of specific information, and the synapse is the mechanism for storing this information. Similarly, Bruer maintains that getting children to store information is exactly what schools should be about; but this is also where neuroscience (Greenough's) gives us little guidance. Bruer suggests that unless neuroscience is ready to reveal critical periods for the learning of domain-specific (or subject matter) knowledge such as math and chemistry, it is safe to assume that there are no critical periods beyond sensory-system development. Like Bruer, Greenough contrasts specific information, which is unavailable in the environment unless made available by the teacher, with sensory information that is ubiquitous in the environment. For Bruer, the contrast translates into the kind of information that needs to be taught by means of direct instruction (is educationally relevant) and the kind of information which requires no teaching. The latter is not what children "go to preschool to acquire." Therefore, according to Bruer, "we should be skeptical of claims that attempt to generalize from what we know about critical periods in brain development to critical periods for the acquisition of culturally transmitted knowledge" (p. 8).

Communication of Scientific Results to Nospecialist Consumers

A major difficulty in many fields of inquiry is communicating scientific results to nonspecialist consumers. For education as a consumer of scientific research, whether such

research is conducted within education or outside the field as in neuroscience. the communication problem is severe enough to have been repeatedly the theme of the annual and other meetings of the American Educational Research Association. The problem has also special significance in education, given that the so-called nonspecialist consumers such as politicians and teachers are vital partners in the educational process. Additionally, this communication problem is compounded by the public's crisis of confidence in education (Schon. 1987). This means that successful communication often requires more than passing on information. To be effective. communication must often change the audience's attitude. level of confidence, willingness to act, and commitment to the cause.

The reform-oriented neuroscience and education movement has already made notable strides toward breaking some of the barriers to effective communication of the results of brain research to teachers, politicians, and the general public. The target article describes this rare avenue of success as a dangerous bridge to cross for "too many people marching in step" (p. 15). Rather than depriving education of this rare opportunity, why not make it yet another "educational moral or policy recommendation" to understand the nature of its momentum. What forces facilitate the communication of scientific results to educational consumers?

One potential source of answers to such questions lies in the recognition that effective communication of scientific research with nonspecialists is more than scientific discourse made simple. It requires a qualitatively different style of communication capable of penetrating many pragmatic barriers that are impervious to scientific locution alone. It is this type of pragmatically effective communication style that the popular neuroscience and education movement seems to

have managed to harness successfully. And it is this type of pragmatic locution that is the real target of Bruer's indiscriminate attack. Understandably, not everything is perfect with the current reform-oriented neuroscience and education movement at this early stage of its development. The solution to any problems that might exist or arise is selective and systematic attention to the particular problems rather than indiscriminate elimination of the entire movement.

One possible difference between formal (or conservative) scientific communication and the communication styles aimed at nonspecialists can be illustrated using Austin's (1962) notion of speech acts. Austin suggested that there is more to a successful act of speech than conveying the (literal) information content of the words used. Thus, a speaker's language utterance is chosen to represent (liberally) a primary focus on the pragmatics of the situation, rather than the formal (or literal) details of the utterance. This focus on pragmatics encompasses three interrelated aspects of a speech act: (a) the particular style chosen by the speaker, (b) the intended interpretation to be produced in the listener, and (c) the intended effect on the listener. For example, a speaker may use the utterance Could you pass the salt (a question about the listeners ability rather than a command to perform an act); the listener at the table interprets this **question** as an **indirect request for action** (rather than a direct request for information); and the listener finds this request for action to be more palatable than the (literal) command Pass the salt! It is the third aspect of communication (the willingness-changing effect on the listener or consumer) that the formal (or literal) language of science sometimes sacrifices as it struggles conservatively with the tedious details of accuracy and truth; and it is this aspect that must NOT be ignored in communication with nonspecialists.

Throughout the target article. Bruer criticizes the information content of popular educational writing with such statements as ". . . readers outside the field should be aware . . ." (p. 6), "[n]euroscientists know [and others don't] that it makes little sense to speak . . ." (p. 8), ". . . Greenough is [and others are not] careful in interpreting his findings" (p. 9), and "[t]his both oversimplifies and misrepresents what we now know about critical periods in neural development" (p. 8). Judged by its information content alone. the utterance Can you pass the salt may be said to oversimplify, inadequately represent, or even misrepresent the request for action it is intended to convey. Given the pragmatics of the situation, it may be considered an appropriate fit. By the same token, the primary focus of the evaluation of the neuroscience and education alliance must be on its pragmatic impact rather than conservatively on the specific details of its information content.

Beyond Specific Knowledge

Bruer's analysis, as well as Greenough's neuroscience, relies heavily on the view that learning is internalizing specific culturally transmitted information. Then, the automatic tie with neuroscience is that the synapse is the mechanism for storing such knowledge. As a result, the brain and education bridge becomes inconsequential, at least as far as educational pragmatics are concerned, because it is reduced to the already well-understood hypothesis that schooling is the transmission of specific knowledge to children. Alternatively, the synapse may be serving a nonspecific purpose with an entirely different role in overall brain functioning than storing specific information. On an evolutionary scale, the specific information involved in the multiplication table, for instance, may be too recent a phenomenon

to have found its way into the brain hardware. In general, the brain may have simply not yet had enough relative experience with culturally transmitted knowledge to sculpt specific critical periods for it, even if such were to be expected or necessary. On the other hand, evolution has had plenty of time to muster resilient nonspecific forces of adaptation for dealing with all kinds of specific challenges ever-changing environments never cease to present. One intriguing example of such adaptive capability is the capacity of organisms like insects to develop immunity to modern pesticides as exotic and as specific DDT. Another example is the capacity of humans, as well as other animals, to adapt to such conditions as weightlessness and carry on daily routines in space (e.g., moving around, sleeping, drinking in the space shuttle). Clearly, the biological mechanism for handling specificity is at least as likely to be a nonspecific adaptive bias of the same kind (Easter, Purves, Rakic, & Spitzer, 1985).

There is much neuroscience behind the view that the brain uses nonspecific mechanisms to deal with specificity. The target article does not consider this literature. Consider, for instance, the sequential ordering of motor behavior as might occur in walking or the production of specific language utterances. Speech production is as specific and sequential as any behavior can ever get in that particular sounds, syllables, words, phrases, sentences, and so on appear to follow one another. The biological mechanisms that work together to make this possible need not be correspondingly specific (Lenneberg, 1967). According to Lashley, a speech utterance cannot be a specific chain of associations (Lashley, 1951), mainly because an individual movement, to cite Lenneberg, "is part of not just one but many different coordination patterns" (p. 14). Following this kind of reasoning, Lenneberg (1967) presented

an impressive amount of data in support of the hypothesis "that the general, nonspecific states of maturation of the brain constitute prerequisites and limiting factors for language development. They are not its specific causes" (p. 169). Or, again, "it is not so much one or another specific aspect of the brain that must be held responsible for the capacity of language acquisition but the way the many parts of the brain interact" (p. 170). Thus, the hypothesis that the synapse is the mechanism for storing specific information is only one alternative in the field of neuroscience.

The educational implications of the specific and nonspecific perspectives on the development of brain connections are as dramatically different as the perspectives themselves. According to Goldman-Rakic (1987):

> A lack of sequence for sensory, motor, and associative functions at first may seem heretical in that the notion of hierarchical staging for these processes is so firmly entrenched in psychology, neurology, and biology [as well as education]. However, on deeper analysis, concurrent functional development is a very appealing notion from both a biological and psychological point of view as it emphasizes the integrated nature of behavior and the fact that few functions of the organism, however simple, are carried out by one part of the brain in isolation from all other parts. (p. 616)

Bruer isolates the knowledge-transmission view of education and equates it with education as a whole. He also separates synaptogenesis from neuroscience in general, limits it to the development of sensory systems (further isolation) following the work of Greenough but not others (yet more isolation). He, then, puts the two together to build the case against the

brain and education as a whole, claiming that we do not know yet enough to determine if there are critical periods for specific subject-matter knowledge (isolation again). All of this gives the impression of removing all the limbs of an animal and asking it to run. The ultimate isolation comes with such illusive words as "enough" or "yet," which refer to some vague quantity of knowledge, or some equally vague point in time, to be (or not to be).

Goldman-Rakic's quotation cited above suggests that the tendency to isolate is as interdisciplinary as the conservative orientation. This tendency has also been identified as one of the most seductive and damaging problems in education (Salomon, 1994, 1995). Similarly, Bloom (1984) also noted that in the course of the several decades since the publication of his cognitive taxonomy of educational objectives (Bloom, Englehart, Furst, Hill, & Krathwohl, 1956), educational practice has seldom moved beyond knowledge, the lowest of the six levels of the taxonomy. The focus on knowledge is exactly what Bruer's conservative education prescribes. On the other hand, going beyond knowledge seems to be the essence of the mission of the reform-oriented neuroscience and education movement. The neuroscience implied in the Goldman-Rakic (1987) quotation offers a clear indication of the direction education must take to accomplish this mission. The reform efforts must "emphasize the integrated nature of behavior and the fact that few functions of the organism, however simple, are carried out by one part of the brain in isolation from the other parts" (p. 616). In other words, the emphasis on whole-child education must replace the current focus on the mere internalization of external knowledge that has dominated the institution of education for so long.

The Default Alternative

Prevention versus Remediation

In a recent television interview. Ross Perot. the former independent presidential candidate, was asked about affirmative action. The answer he gave was a most unexpected one. In an obvious allusion to the relevant neuroscience literature, he said that if we put a patch on the eye of a newborn animal to prevent the eye from making its connections to the brain. no reasonable amount of remediation afterwards can give back the animal its eye sight. Keep off the patch. and the animal will see for a lifetime. Similarly, when impoverished environments put patches on children's brains for years. no amount of affirmative action is going to help afterwards. Prevent the patches today (e.g., by giving children the right kinds of environment and support), and affirmative action is less likely to be necessary tomorrow.

Affirmative action is a direct measure for curing the symptoms of some very fundamental problems that exit in our society. Ross Perot's response suggests a philosophy of prevention through elimination of the real causes of these problems. This philosophy of prevention is also a major theme in the neuroscience and education movement that Bruer wishes to halt or redirect. This theme comes across clearly even in several of Bruer's own quotations from the neuroscience and education literature. The following excerpt from the Carnegie Task Force (1996) report is an example:

> [The] age span from three to ten [is] absolutely crucial for children's optimal learning and development. These years offer families, communities, and schools critical intervention points for helping children develop knowledge and skills, positive attitudes

toward learning, healthy behaviors, and emotional attachments of powerful and enduring significance. If these opportunities are squandered, it becomes progressively more difficult and more expensive to make up for the deficit later on. (Carnegie Task Force, 1996, p. 10, cited by Bruer, p. 5)

Bruer takes issue with the rhetorical, scientific, and other details of the neuroscience and education movement, masking the salient prevention theme that characterizes its campaign. By contrast, the ubiquitous theme throughout the target article is remediation. This is particularly evident in Bruer's choice of the innovative remedial curriculum of Griffin, Case, and Siegler (1994) as an illustration for his preferred bridge between cognitive psychology and education, stating that the "curriculum meets the special needs of children who may not have acquired the mental number line before entering school" (p. 12). Another example of the target article's philosophy of remediation at the expense of prevention is evident in his characterization of the degree of plasticity of sensory-system critical periods. Plasticity sets the stage for any necessary remediation. Thus, "after the period of sensitivity to deprivation, . . . [w]ith appropriate training and therapy, at the appropriate time, cats, monkeys, and humans can recover near-normal visual function following periods of deprivation" (p. 8).

Critical Periods and Formative Postnatal Development

Greenough's neuroscience fixes the concept of critical periods firmly into the information-storage metaphor. According to Greenough (1987), the synapse is a memory mechanism (a biological chip, so to speak). It grows to store knowledge as the information processing system receives it from the environment. In this view, the concept of critical

periods in child development contrasts starkly with plasticity defined as the life-span capacity to store information. As an example, Bruer identifies "our ability to acquire new vocabulary ([for] which [no critical period exists because this ability] continues throughout our lifetimes (Neville, 1995)" (p. 8). Thus, "many of the effects of experience upon behavioral development do not appear to exhibit the relatively strict age-dependent character [of the critical periods] associated with early sensory-system development" (Greenough et al., 1987, p. 546). In other words, the plasticity associated with the notion of information storage implies that no critical periods exist outside the realm of early sensory-systems development.

Conservatively interpreted, the concept of critical periods implies an all-or-none capacity, one that exists during a particular time window and disappears afterwards. Therefore, if we assumed that the learning of X (or, rather, the storing of X in brain synapses) is possible any time during the life span, it would follow that no critical period exists for learning X. If we generalize this reasonable argument to all X, we encounter a troubling implication: that there is nothing special about learning during the entire time window called childhood. The problem gets more complex if we assume that (a) X is culturally-transmitted knowledge, (b) the brain, like a computer, treats all X in the same way, and (c) schools must do no more than transmitting X to children. The brain becomes synonymous with a computer; and the natural balance in the ecological relationship that evolution has forged between biology and environment (see, e.g., Scarr, 1993) suddenly loses its special significance altogether.

From a reform-oriented perspective, the concept of critical periods has a number of pragmatic, if not yet demonstrably logical, implications. First, it suggests that children are

children until they become adults and that they must go through many formative years of postnatal development to become adults. Second, it implies that the brain, unlike computers, learns not all X in the same way. Formative postnatal development (FPD) may be described as the period that extends from birth to the time the child reaches adult levels of growth and maturation. For humans, FPD is commonly viewed as approaching closure toward the end of the second decade of life. As already noted, synaptic development in some parts of the brain is still in FPD during late adolescent years, as are many other aspects of the brain such as the development of myelination and neurotransmitter systems (Dawson & Fischer, 1994; Mize & Erzurumlu, 1996; Reynolds & Janzen, 1989). Closely interacting with these brain systems are emotional development, cognitive development, social development, the development of language, sexual development, and the development of critical thinking, to name a few. Therefore, formative postnatal development years are a critical era in the life of the individual, who is potentially at risk in many fronts during these years.

According to Bruer, sensory-system synaptogenesis represents a critical period. Later, there is no critical period, and indeed nothing special about development, because internalizing things like the lexicon, math, and science require no set timetable. Similarly, Greenough and his colleagues (Greenough, 1978; Greenough et al., 1987) distinguish between sensitive periods in sensory-system development for experience-expectant information storage (or experience-expectant synaptogenesis) and experience-dependent information storage during later development and adulthood (or experience-dependant synaptogenesis). Another way of looking at the difference is that experience-expectant development (or critical periods) is

irreversible with later experience (the learning opportunity is lost for ever); but experience-dependent learning (or information storage plasticity) is reversible (if it does not occur now, it can occur at some later time). In other words, because the critical-period window of opportunities is narrow, experience-expectant development is, in principle, subject to threats to normal development. By contrast, experience-dependent learning is not subject to such threats because its window of opportunities is assumed to stay open for the entire life span. What is not learned today can be tomorrow, which is why Greenough's neuroscience of information storage and Bruer's knowledge transmission education discount the evidence that "the prefrontal cortex, or at least the middle frontal gyrus, matures throughout [formative postnatal] development" (de Haan, Luciana, Malone, Matheny, & Richards, 1994, p. 161). For them, the frontal cortex maturation does not constitute a critical period in child development, perhaps because this area is a storehouse of culturally-transmitted information.

While irreversibility and plasticity are often the stated criteria, the real criterion is whether the corresponding effects (e.g., loss of vision or poor performance on a math test) can be readily observed. If corresponding outcomes are subtle, if they cannot be readily observed and manipulated, then they are assumed to be reversible and age-independent. Thus, the critical versus noncritical determination rests entirely on the difference between the sensory deprivation framework, which is highly sensitive to irreversibility as an observable measure, and environmental complexity methodology, which is not so sensitive to observable measures of reversibility (see Greenough et al., 1987).

The environmental complexity paradigm is an information theory concept. In this

paradigm, complexity is the amount of information available in the external stimulus (Shannon & Weaver, 1949); learning is specific information storage; and how much is learned is a quantitative function of stimulus complexity (Berlyne. 1960). If something is not learned now, it can be at some later time. Related to synaptic development, Greenough et al. (1987) reviewed studies that manipulated stimulus complexity in laboratory rats. Rats can be raised in increasingly complex environments ranging from the least complex individual cages (IC), to more complex social cages (SC) each housing a small group of rats, to most environmentally complex (EC) group cages filled with toys and obstacles. Accordingly, if we assume that information storage is a linear function of the amount of stimulus complexity (Berlyne, 1963) and that information storage requires new synapses, then we can predict a linearly increasing pattern of synaptic connections in IC, SC, and EC rats, respectively. In this paradigm, irreversibility (which defines the critical period concept) does not play a role because the presumed experience-dependent nature of synaptic development ensures the growth of the synapse whenever external information is made available. While this is an ideal framework for Bruer's conservative information-transmission view of education, it is not so ideal for investigating the critical nature of formative postnatal development years. Moreover, the environmental complexity paradigm is at odds. with the reform-oriented mission of the neuroscience and education movement that sees the direct link between brain development and education during the formative brain development years as being a great deal more than information transmission.

Plasticity, Flexibility, and Stability

It is noteworthy that even in the original Wiesel and Hubel (1965) study, it was the shift in dominance from the deprived eye to the normal eye, rather than the loss of information or information storage capability, that made recovery of the deprived eye "irreversible." The selective adaptation mechanism implied by this shift-of-dominance phenomenon is such a ubiquitous occurrence in the development of the nervous systems across species that several leading neuroscientists have based major theoretical perspectives on it (Changeux & Danchin, 1976; Edelman, 1978; Goldman-Rakic, 1987). In fact, recent developments point to a remarkable capacity of the functioning brain as the only system known to be simultaneously capable of inordinate stability and unrestrained flexibility, the two essential conditions for negotiating adaptive shifts-of-dominance (gear change, so to speak) in a dynamically functioning system. The central nervous system seems to accomplish this by (a) maintaining dynamic patterns of ongoing brain activity that are (b) remarkably in tune with moment-by-moment stability and change both inside and outside the system.

Edelman (1987) describes the shift-in-dominance hypothesis arguing that selection is a competitive process in which one neuronal group may gain dominance over another by actually capturing cells from other neighboring groups by differentially altering the efficacy of their synapses. This process, "in which groups that are more frequently stimulated are more likely to be selected again, leads to the formation of a *secondary repertoire* of selected neuronal groups which is dynamically maintained by synaptic alterations" (pp. 46).

The shift-in-dominance view allows reorganizational flexibility or, in other words,

stability in the midst of plasticity. Going back to the Wiesel-Hubel (1965) study, stability manifests itself as apparent irreversibility of the pattern of dominance (of one eye over another); and plasticity means shift in dominance. under suitable contextual conditions, from one dynamically maintained pattern to another. The patterns, sensory or otherwise, are inordinately stable and enduring; but they are also capable of flexible reorganization. This explains why vision can return to the deprived eye when appropriate measures are taken to counteract the enduring pattern of dominance. The information storage hypothesis would suggest that irreversibility entails loss of specifically localized, as well as time-locked, plasticity because the to-have-been-formed synapses have deteriorated in the "regions involved in the information-processing activity that [would have] caused their formation" (Greenough et al., 1987, p. 549). This time-locked. storage-sensitive view of plasticity is very different from the notion of plasticity as reorganizational flexibility.

A more prominent example of shift in dominance, but with striking parallel properties with the case of sensory-system synaptogenesis is the gradual shift that occurs in language function from one brain hemisphere to another. Lenneberg (1967) reviewed the evidence from massive lesions to either of the two brain hemispheres. Before the onset of speech, the two cerebral hemispheres of the brain, like newborn eyes, seem to be roughly equipotential; and for some time after, they are equal participants in language development. Then, as development progresses (and stability tightens its grip), the right hemisphere becomes less and the left more involved in speech. However, the right hemisphere might maintain its language function if massive lesions prevent the left hemisphere from taking over. Lenneberg

supplemented the evidence from the study of brain lesions with findings from structural changes in the brain, changes in its biochemical composition, and changes in electrophysiological activity. He concluded that:

> All of the parameters of brain maturation studied show that the first year of life is characterized by a very rapid maturation rate. By the time language begins to make its appearance about 60% of the adult values of maturation are reached. Then the maturation rate slows down and reaches an asymptote at just about the same time that trauma to the left hemisphere begins to have permanent consequences. (p. 168)

Lenneberg postulated a critical period that begins at birth and ends with puberty. He reached his conclusion based on the findings suggesting that language loss due to brain trauma was reversible at a declining rate during this period and irreversible afterwards. He assumed that the underlying cause was permanent specialization of brain hemispheres, the left hemisphere for language and the right hemisphere for other things. However, more recent findings in brain research suggest that the gradual increase in the enduring stability of dynamically-maintained neural groups is responsible, in the midst of the inherent flexibility of the functioning brain (Lerner, 1994), for the apparent irreversibility of aphasic patterns. Thus, as Easter, Purves, Rakic, & Spitzer (1985) describe, it is "the prolonged synaptic malleability generated by these long-term competitive interactions [that] may be the basis of the extraordinary ability of the human nervous system to adapt to an ever-changing external environment" (p. 510).

Given the two different ways of viewing plasticity, it is not surprising that the target

article has overlooked this body of research that directly relates to synaptic development and critical periods. The research is irrelevant to the conservative view of education as knowledge transmission and incompatible with the information storage hypothesis of synaptic plasticity. On the other hand, it is this kind of research that is most in tune with the reform-oriented neuroscience and education movement. Interestingly, from the conservative viewpoint of education as knowledge transmission, Bruer's conclusion is indeed correct. Developments in neuroscience have very little to offer the view of education as knowledge transmission and the theory of plasticity as the life-span capacity of the synapses to store knowledge. For example, before outlining his theory of neural group selection, Edelman (1987) noted that his "consideration of certain structural and functional features of the complex nervous systems points up some of the difficulties that must be faced by information processing models of the nervous system" (p. 37). Greenough's neuroscience, while compatible with the information transmission perspective, tells us very little beyond what conservative education already knows about direct instruction of culturally transmitted knowledge.

Aspects of Formative Postnatal Development

Why does it take nearly two decades for the human offspring to approach adult levels of maturation? The answer is likely to have much to do with the fact that multiple interdependent sources must contribute simultaneously to FPD. Scarr (1993) identified four different kinds of influences on individual development: genetic activity, neural activity, behavior, and environment. Multisourceness, interdependency, and the complexity of the system can explain why FPD takes time. They also imply that education cannot afford to treat

FPD as anything less than a special. if not critical. era. By limiting the role of education conservatively to culturally transmitted knowledge, the target article sacrifices the contribution of other sources to human development.

Bruer's article is not the first time the information storage hypothesis has led to the conclusion that the brain is dispensable. In 1967, Niesser allocated the entire first chapter of his book, Cognitive Psychology, which re-popularized the concept of information. to arguing that computer-inspired information storage is possible without having to resort to the brain at all. Thus, severing with the brain is a logical consequence of adopting the computer-inspired information storage theory. It is not really the result of how much we know about the brain.

Severing with the brain also entails a clean break with evolution, another necessary consequence of the information storage theory. Potentially fundamental work of evolution (e.g., synaptic overproduction) quickly grows epiphenomenal. If information storage is all there is to child development, why is it that for so many species in the animal kingdom "the individual confronts the world before his ontogenetic processes are completed" (Garstang, 1921, p. 6)? The so-called synaptic blooming-pruning phenomena might play a critical role in the formative process of adaptation toward a fully functioning adult. However, for the information storage hypothesis, the phenomena comprise a paradox. Since the time of G. Stanley Hall (1904, see, e.g., pp. 489-491), it has been known that memory improves steadily during the time period Greenough identifies as "later" development. During the same time period, the number of synapses per neuron also steadily decreases. How could this be if the synapse is a memory chip ready to store information, as Greenough claims? The explanation

is anything but straightforward. Bruer and Greenough deal with this problem implicitly by ignoring synaptic pruning and by squeezing synaptogenesis, in particular, and the role of evolution, in general, into the brief period of sensory-system maturation. Bruer states that "it is as if evolution has resulted in the neural systems that expect to find certain kinds of stimuli in the environment in order to fine-tune their performance (Greenough, Black, & Wallace, 1987)" (p. 7). The course of this fine-tuning is seen as fixed in time, and as being innately programmed to expect minimal input.

Another consequence of the information storage theory is a clean break with the environment as an authentic ecological system (Bronfenbrenner, 1979). Neisser (1976) acknowledged this in the introduction of his Cognition and Reality book. Referring back to his 1967 book and theory, Neisser states that the information storage theory has momentum and prestige but it undermines the human nature. The book then goes on to adopt Gibson's ecological approach. For both Bruer and Greenough, the special contribution of the environment is minimal to the development of sensory-system synaptogenesis. Beyond sensory-systems development, there is information extraction, transmission, and storage in the central nervous system (CNS) for both children and adults.

Finally, the focus on information storage and transmission entails a clean break with development itself. According to Bruer, synaptic development is relevant to child development and education to the extent that it can be correlated with concurrent changes in behavioral and information processing capacities. He states, "whatever the course of synaptogenesis in humans, if it has relevance for child development and education, we must be able to associate

this neurodevelopmental change with changes in infants' behavior and cognitive capacities" (p.6). Bruer cites some early developmental milestones, mainly Piagetian sensorimotor development, which correlate with synaptogenesis. He states that ". . . all these are examples of the emergence or changes in sensory, motor, and working memory functions. However, these are not abilities and skills children learn in schools or go to preschool to acquire" (p. 7). The implication is that the developmental correlates of synaptogenesis are not educationally relevant because we do not know how they relate to storing subject-matter knowledge: "the most we can say is that synaptogenesis may be necessary for the initial emergence of these [information storage] capabilities and behaviors, but it cannot account entirely for their continued refinement" (pp. 6-7). Whereas this may be true to some extent, it is too stringent a criterion for determining educational relevance. It is like requiring the development of the functional capacity of the infantile lungs to correlate with changes in athletic behavior and capacity. Naturally, a well-functioning pair of lungs should correlate with future athletic talent and performance; but we end up throwing the baby out with the bathwater if we limit the relationship to contiguous correlation during infancy. In this fashion, the information storage theory undermines the life-span consequences of the formative postnatal development. By contrast, the reform-oriented brain and education movement stresses FPD.

The present discussion of synaptic maturation is in basic agreement with Bruer's article in one respect: that synaptogenesis is not exactly the same as learning, as suggested by some writers in education. However, this does not mean synaptogenesis is limited to sensory maturation or occurs invariably for all normal children--in the same way, stage of

development, and brain regions (see Freedman & Cocking, 1986). Moreover, it is true that evolution has forged concordance between synaptogenesis and natural environments; however, this does not pre-ordain that all childcare and school environments are, without exception, natural places and have the same effects on synaptogenesis. On the contrary, not everything is natural concerning present academic environments. One must question the "naturalness" of environments in which a significant portion of the child population must be given drugs in order to comply to unnatural school conditions and procedures for several hours, day after day, and year after year during the formative postnatal development years. Moreover, the present discussion implies that a more balanced learning condition today is likely to facilitate more optimal patterns of synaptogenesis and, as a result, more optimal functioning during adult lives of tomorrow.

If our criteria are overly stringent, if we limit critical postnatal growth to sensory-system maturation, if we ignore the evolution-tested learning styles of the brain, if we limit the ecological role of the environment to brute information, if we reduce mental functioning to cold calculation, if we separate learning from development, we are likely to deprive postnatal development of its universally recognized nature and role: that it is a formative period with its own survival assets and liabilities (Bjorklund, 1992, 1997) whose purpose is to unite multiple genetic, neural, behavioral, and environmental influences (Scarr, 1992, 1993). Evolution has endowed organisms of all species with this formative period, not for information storage or contiguous performance, but to prepare for competent adult life of the future years.

Increasingly, educators see brain-based education as the only hope for doing justice to

the requirements of the formative postnatal development years. The popular neuroscience and education movement is a timely recognition of this fact. It is also an implicit acknowledgement of the work of evolution and the fact that most other species in the animal kingdom treat FPD as special. Are humans ready to ignore the developmental assets and liabilities of children during this special period? Are we ready to leave children to their own devices under the trampling pace of the stampeding rate of change in modern societies? If we are, we are in danger of making the human race to become the first species to turn its back to its young.

Conclusion

"Can a profession whose charge is defined by the development of an effective and efficient human brain continue to remain uninformed about that brain" (Sylwester, 1995, p. 6)? In 1984, Clore and Vondruska cited William James (1884) and Marvin Minsky (1980) as lamenting that too often researchers resort to we-do-not-know-enough to postpone till tomorrow the difficult problems of today. Clore and Vondruska (1984) added, "there is a great deal of reluctance . . . to get involved with concepts bearing on the nervous system" (p. 307). From where we stand today, the tide has now turned in the direction of the brain. The very fact that Bruer wrote his article is an indication not only of the imminent threat to conservative education but of the strength of the reform-oriented alternative. Perhaps for the first time in the history of education, we are truly faced with the tough challenge of taking the road not taken. It is intriguing to view this dilemma through the eye of the statistician. Bruer insists that our understanding of the brain has not yet reached where it can inform educational practice. The default alternative maintains otherwise. Thus, Bruer's conservative education is

likely to err on the side of what statisticians call the Type I error, where brain understanding can illuminate educational practice but education chooses to remain uninformed. This would amount to closing the door to understanding and potentially sound educational practice down the road. The reform-oriented default alternative is likely to err on the side of the Type II error, where brain understanding cannot yet inform education but education chooses to use brain research. This can only serve to open new doors to later progress.

The default alternative to Bruer's negative conclusion has only recently gained enough strength and momentum to force its way out of its embryonic iron-shell. To appreciate the spontaneous force of this new development, we must consider at least three aspects. First, education is not the only field where the brain is finally making us aware of its presence. Rather, what is a struggling neonate-conclusion in the educational community is presently a healthy toddler in other fields such as engineering, aerospace, computer science, and robotics. Second, fundamental changes in the way scholars are viewing the brain have occurred within the past decade or two. Traditionally, when brain researchers examined the brain, they saw a kind of mushroom for storing knowledge with a stem, middle, and top consisting of layers, regions, lobes, ridges, and valleys. Now, when we examine the brain, we see a dynamically functioning biological ecosystem, the finest piece of art that evolution has ever sculpted, comprising living subsystems and microsystems. In such a biological ecosystem, nothing can occur without system-wide consequences. As noted by Goldman-Rakic (1987), "with so many complex mechanisms requiring an orchestrated plan of evolution, alteration of any one of these processes could set in motion a whole chain of events" (p. 253). Finally, when engineers,

computer scientists, physicists, and other researchers consider the brain, they are not expecting specific techniques, ready-made, from particular lines of neuroscience research. On the contrary, they cast their nets widely and deeply for interdisciplinary insights on how we can learn directly from the brain itself, as the ultimate master of problem solving in the natural world. Previously, our strategy has always been to go to the mind (that the brain creates) for answers. In many fields now, researchers choose to go directly to the source to learn about the brain's own evolution-tested ways of solving natural problems. For education, herein lies the essence of the challenge of the road not taken. Within this context, the characteristic timidity of the conservative research community, in the guise of being scientifically accurate, has been replaced with a vigorous boldness, which parallels such fields of inquiry as space travel.

So what are the implications for education? As Goldman-Rakic (1986) put it, "the answer is 'everything'" (p. 253). We can no longer afford to rely on how we *think* people learn. We must turn to the brain to discover its evolution-tested ways of learning, to imagine and conceive how the brain solves the problems of self-regulation, self-maturation, learning, and development in what Schon (1987) called the slimy swamp of the natural world.

The rise of the default alternative impacts another important problem. Schon (1987) commented on the crisis of confidence in education. With the wisdom of the default alternative rallying science, politics, public opinion, and media, we are in the midst of a rare opportunity to face up to the challenge of finding a solution. However, before solving the public's crisis of confidence in education, education must resolve the crisis of confidence in itself. The default alternative to Bruer's negative conclusion entails a positive conclusion that can help in both

fronts. Three decades ago, John F. Kennedy made an appeal to scientists from diverse backgrounds. He called upon them to work above their differences and together in order to successfully land human beings on the moon and return them to the earth safely; the rest is an old story. In his 1997 State of the Union Address and repeatedly on other occasions, Bill Clinton, along with Hillary Clinton, has been making the same kind of appeal about brain-based education. Now is not the time to flee from this challenge. Rather, it is the time for us all to join forces to rise up to this challenge as a unified body, open to innovations and new discoveries. We must not let what we do not yet understand frighten us. We must approach this challenge systematically, with a science that is suitably rigorous as well as relevant and not rigidly rigorous at the expense of relevance. Simultaneously, we must not be so closed minded to view the world through one dominant eye as did the Wiesel and Hubel kittens. "If we can't offer informed leadership on the complex educational issues arising from current brain theory and research, we can expect that other people—perhaps just as uninformed as we are—will soon make decisions for us" (Sylwester, 1995, p. 6).

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